SIMULATING A BILATERAL TELEOPERATION SYSTEM USING MATLAB AND SIMULINK

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Abstract

Teleoperation provides a human-machine interface that allows an operator to control machines at a large distance. It has recently been the subject of a significant amount of research in the robotics community. Teleoperation can also provide an instructor with an excellent motivating example for a control systems course where it can serve as a platform for introducing several key controls issues such as noise compensation and time delay. Computer packages such as Matlab and SIMULINK are readily available in most engineering schools for simulating teleoperation systems. In this article, SIMULINK is used to present a case study of a simple teleoperation system. Initially, a PI controller is introduced to control a simple bilateral teleoperator model without noise or time delay. It is then shown that the inclusion of time delay can significantly affect the system performance and can even cause the system to become unstable. A relatively new technique called the wave variable method is then used to stabilize the system for any fixed time delay. Lastly, recommendations for further educational projects involving teleoperation are given.

Introduction

Since the introduction of the first modern master/slave manipulator in the late 1940's, teleoperation systems have been used for a number of different tasks, e.g., handling toxic or harmful materials, operating in remote areas such as undersea or space, and performing tasks that require extreme precision, and will continue to play an increasingly important role for such applications in the future [4]. Recently, teleoperation has gained greater public awareness through the Mars Rover project. Future applications include robot surgery in remote communities, war zones, and disaster areas and teleoperation over the Internet. There are also numerous educational applications [9].

During teleoperation, the operator typically uses a visual display and a "master" manipulator (e.g., a joystick) to manually control a remote "slave" device such as a robotic arm. The teleoperation system consists of a human operator, the master, the communication channel, the slave, and the environment. To improve the task performance, the contact force of the slave with the environment can be reflected back to the operator. Adding force feedback to a teleoperation system provides the operator with increased awareness and can considerably improve his or her ability to perform complex tasks, particularly when visual information is limited. In this case, the system is called a bilateral teleoperation system.

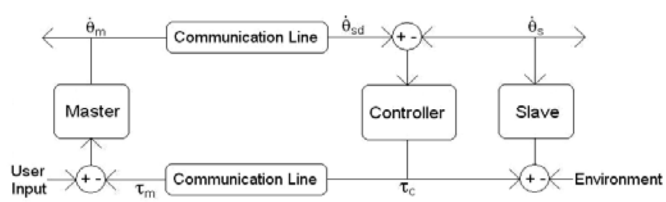

Figure 1: A bilateral teleoperation system.

Figure 1 is an illustration of a haptic bilateral teleoperation system. The haptic, or force feedback, interface provides a kinesthetic link between the operator and a virtual environment giving the user the ability to actually feel the environment surrounding the slave manipulator. The goal is for the slave device to track the master's behavior with respect to force, position, and velocity. Under ideal situations, this goal is easy to accomplish. However, when teleoperation is performed over a large distance, or when using a slow communication channel, time delay appears in the information transmission between the local and remote environments. This can cause a serious degradation in system performance. Time delay can also be quite irritating to the user, particularly when the user is forced to adopt a "move-and-wait" strategy, whereby a small movement is made and the operator waits to observe the results of the movement before committing to further action. Even more serious, time delay can cause a force feedback system to become unstable. System noise can also be problematic [1].

These issues are important subjects of ongoing research in the area of bilateral teleoperator control. Recent results in the area are promising, and some of the techniques are sufficiently developed now that they are suitable for inclusion in undergraduate and first year graduate courses on control systems. The goal of this paper is to describe one of the most promising bilateral teleoperation control techniques that is particularly suitable for educational purposes. While a significant amount of effort and expense would be required to construct and use actual teleoperation hardware, the material proposed in this article only requires software models that can be easily implemented using readily available computer packages such as Matlab with SIMULINK. Throughout the paper we use Matlab and SIMULINK, and we assume that the reader is familiar with these software packages; however, other similar control system simulation software can be used.

The next section introduces a simple model of a bilateral teleoperation system operating under ideal conditions. In this case, a simple PI controller will suffice. After simulating the ideal case, we introduce the student to some "real world problems" such as noise and time delay. The problem of compensating for time delay in the system is addressed by implementing a passivity-based approach called the wave variable method. Lastly, conclusions and recommendations for additional exercises to illustrate teleoperator control issues appear.

Building a Matlab and SIMULINK Model

Initially we will use the following linear model for the equations of motion for the master and slave manipulators, respectively,

$$\begin{aligned} \tau_m &= J_m\ddot{\theta}_m + B_m\dot{\theta}_m \\ \tau_c &= J_s\ddot{\theta}_s + B_s\dot{\theta}_s \end{aligned} \tag{1}$$

where τ_m, τ_c are the input torques, J_m, J_s are the inertia terms, and B_m, B_s are the damping terms of the system being simulated. For the simulations shown in this paper the following values were used: J_m=J_s=4 Kg·m^2 and B_m=B_s=2 Kg·m^2/s. To determine the force necessary to move the slave, the following simple PI-controller is used:

$$\tau_c = K_P e(t) + K_I e_I(t) \tag{2}$$

where $e(t)$ is the difference between the desired slave velocity $\dot{\theta}_{sd}(t)$ and the actual slave velocity $\dot{\theta}_s(t)$, $e_I(t)$ is the integral of the error, and K_P and K_I are the proportional and integral gains of the controller, respectively.

The SIMULINK model of the teleoperation system requires only a few simple blocks as shown in Figure 2. For the master and slave, the transfer function block is used. The PI-controller for the system consists of several simple blocks. A gain block for the proportional gain K_P and another gain block in series with an integrator block for the integral gain K_I are added together in parallel to form the controller. For the input to the system, any source block may be used; for the simulations shown a step function block was used and it was assumed that the slave was in free space so the environment input was zero. Since the outputs of the master and slave transfer function blocks are velocities,

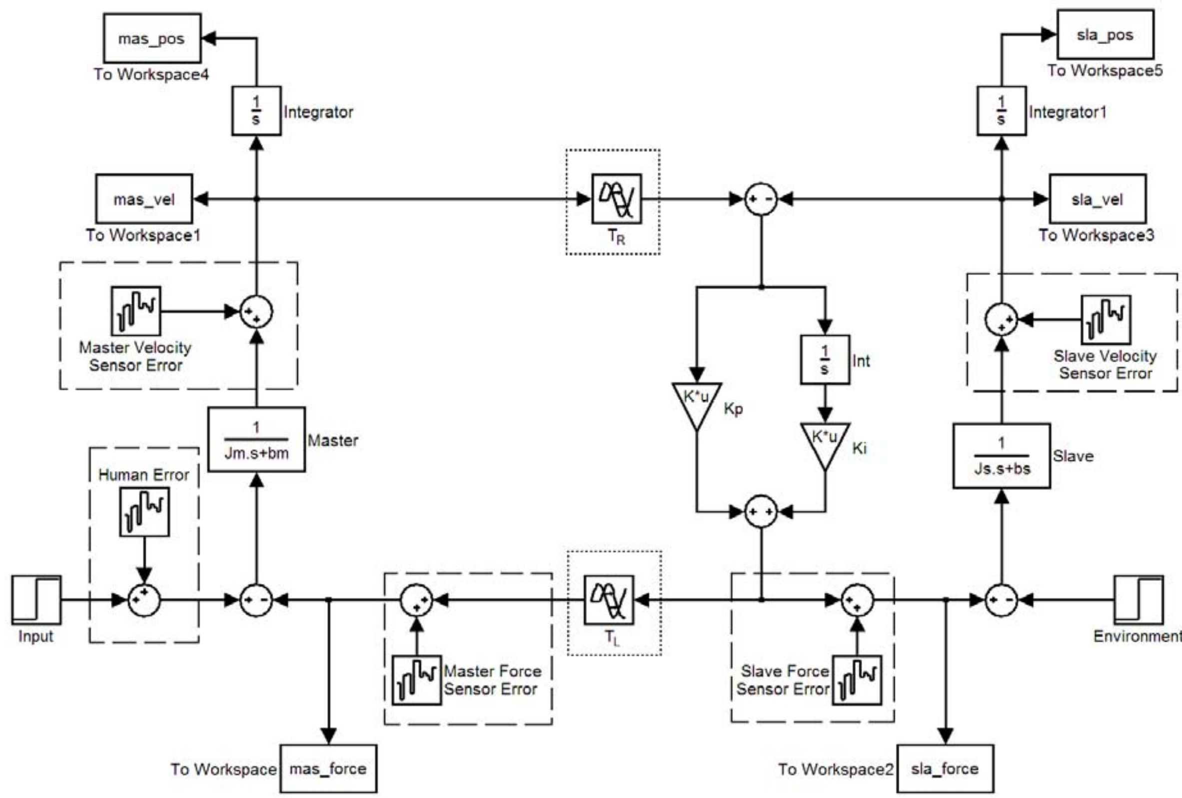

Figure 2: SIMULINK block diagram of a bilateral teleoperation system. The blocks inside the dashed lines represent additive noise while the blocks inside the dotted lines represent time delay.

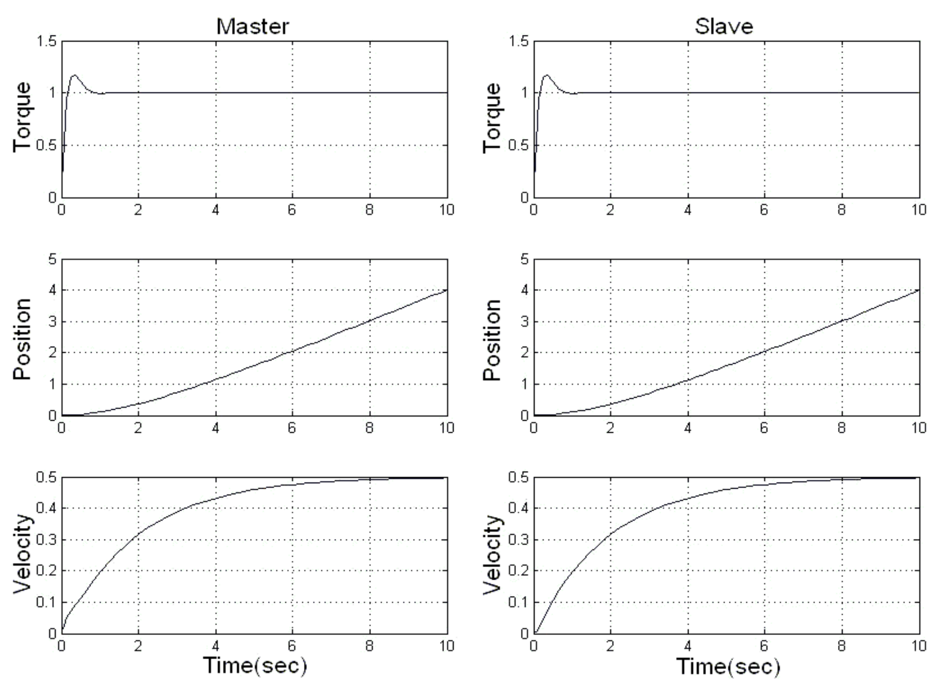

Figure 3: Torque, position, and velocity data for the simulated model of a bilateral teleoperation system.

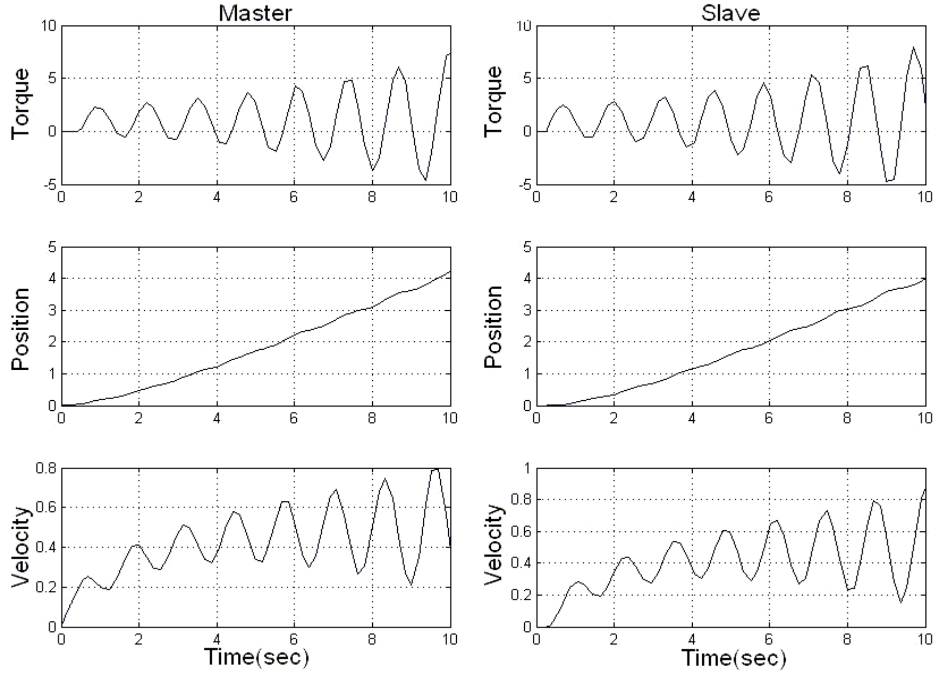

Figure 4: Torque, position, and velocity data for the simulated model of a bilateral teleoperation system with a time delay given by *2T=500msec*.

integrator blocks must be used to obtain position information. For access to the output data, six "to workspace" blocks were used. Each block was given a specific variable name that was saved in the Matlab workspace. Once the SIMULINK simulation is executed and the output data are stored, another Matlab routine plots the data. This file reads in all of the data and conveniently displays the variables of interest; an example of this is shown in Figure 3. In this case we have chosen to display the torque, position, and velocity data for both the master and slave in a side-by-side comparison. Also, the data can be used to determine other quantities such as torque, position, and velocity difference, simply by subtracting the slave data from the master data.

As mentioned earlier once a problem like noise or time delay is added to a system, the performance degrades substantially. In fact, if the time delay is sufficiently large the system will become unstable. Noise can be added by including the blocks shown inside the dashed lines in Figure 2. An approach to controlling a bilateral teleoperation system in the presence of noise can be found in [1]. In this article we will focus on time delay. Time delay can be implemented by including the blocks shown inside the dotted lines in Figure 2. For all of the simulations shown in this article we assume that $T_R=T_L=T$ where T_R is the delay from master to slave and T_L is the delay from slave to master. In this case, we refer to the total round trip delay as *2T*. The same system in Figure 3 was simulated with *2T=500msec*, and the results are shown in Figure 4. As can be seen, the system quickly became unstable. The next section describes a solution to the problem of time delay by implementing the wave variable method.

Compensating for Instability Due to Time Delay

One of the major problems that can be found in bilateral teleoperation systems is time delay. Over relatively short distances, the time delay may not be noticeable; however, when the master and slave are located at a far distance from each other, time delay is no longer negligible. In the case of space teleoperation the roundtrip delay can approach *6sec,* and surface to deep ocean transmission can take anywhere from seconds to minutes depending on depth and mode of communication [10]. Until relatively recently [3], it was thought that time delay precluded the use of force feedback in such cases.

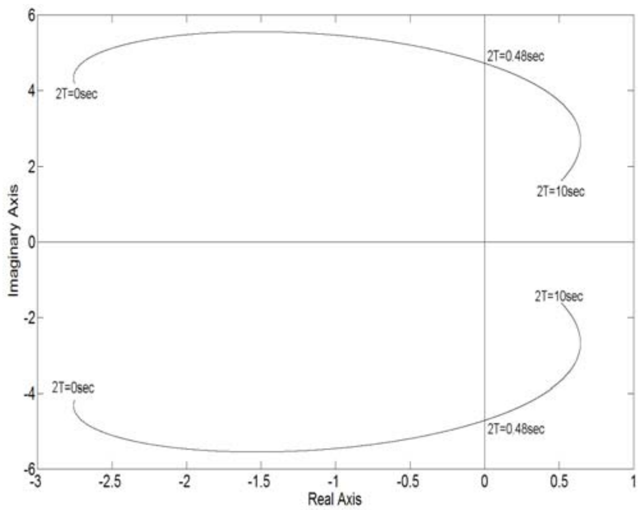

Figure 5: Pole-zero plot of a teleoperation system with a time delay ranging from *2T=0sec* to *2T=10sec*. With no time delay, the system is stable, but as the time delay increases, the system becomes unstable.

Time delay in a control system introduces a phase lag, which in turn degrades the system performance and can cause instability. Figure 5 shows the effect that time delay has on the location of the poles of the transfer function of the original system described in the previous section. The figure was generated by including a Padé approximation for the time delay in the transfer function of the overall teleoperation system and using a 'for' loop to gradually increase the amount of time delay in the system from *2T=0sec* to *2T=10sec*. As the time delay is increased, the poles of the system quickly move to the right and cross over into the right half plane indicating that the system is no longer stable. A Matlab subroutine to generate Figure 5 is relatively straightforward to write, and students should be able to easily reproduce the figure.

In the late 1980's, Anderson and Spong [3] attributed the instability associated with time delay to a non-passive communication block and found that it is possible to stabilize a force reflecting teleoperation system that has a time delay by exploiting scattering theory. Later, Niemeyer and Slotine [7] presented the wave variable method in a more intuitive, physically motivated formalism based on passivity. In the wave variable method, wave variables are used in place of more conventional power variables such as velocity and force. It can be shown that that by transforming forces and velocities into wave variables for transmission along the communication channel, systems could remain stable for any fixed time delay. Several researchers including Munir and Book [5] and Niemeyer and Slotine [8] have addressed the issue of stabilizing systems with variable time delay by incorporating predictors into the system along with a conventional wave variable controller. This technique was successfully implemented on a teleoperation system that used the Internet (which is subject to variable time delay) as the communication channel.

The wave variable method is based on passivity, which is related to the intuitive physical concepts of power and energy. The concept of passivity provides a simple and powerful tool for analyzing the stability of a nonlinear system. It is based on the intuitive notion that a system is passive if it absorbs more energy than it produces. Space limitations do not allow us to provide a detailed discussion on passivity theory here. Instead, we will give only a quick description of the most important points of passivity and scattering theory as they relate to wave variables and refer the interested reader to reference [11], which provides an excellent introduction to a wide variety of nonlinear system concepts including passivity theory, and reference [6], which provides more details on the role of passivity in the wave variable method.

In the passivity formulation, one defines a power quantity P_{in} entering the system as the scalar product between the input vector **x** and output vector **y** of the system. Not unlike the relationship between Lyapunov functions and energy, this quantity may or may not correspond to a physical power. Using the power analogy, the input power should be stored or dissipated in the system. More specifically, let E_{store} be a lower bounded energy storage function and let P_{diss} be a non-negative power dissipation function. The system is passive if it satisfies

$$P_{in} = \frac{d}{dt} E_{store} + P_{diss} . \tag{3}$$

If the power dissipation is zero for all time regardless of input or output, the system is said to be lossless; however, if the non-negative power dissipation, P_{diss}, is positive during any power transfer, then the system is said to be dissipative.

Passivity is a sufficient condition for stability. One particularly nice feature of passivity is the important property that if multiple passive elements are connected together, the resulting system is also passive. This ensures that a connection of passive systems remains stable.

The stability of a teleoperation system can be proven using scattering theory [3]. Given a transfer function $G(s)$, the stability of the system is related to the norm of the scattering matrix

$$S(j\omega) = [G(j\omega) - I][G(j\omega) + I]^{-1} . \tag{4}$$

More specifically, the system is passive if and only if $\|S\| \le 1$ where

$$\|S\| = \sup_{\omega} \|S(j\omega)\|_2 . \tag{5}$$

The norm on the right of equation (5) is the induced 2-norm, i.e., $\|S(j\omega)\|_2 = \sqrt{\lambda_{\max}\left(S^*(j\omega)S(j\omega)\right)}$ where $S^*(j\omega)$ denotes the complex conjugate transpose of $S(j\omega)$ and $\lambda_{\max}(A)$ denotes the largest eigenvalue of the Hermitian matrix A.

To the see the difficulty caused by time delay, suppose that the communication lines in Figure 1 both have a *Tsec* time delay. The transfer function relationship across the communication lines is then given by

$$\begin{bmatrix} T_m \\ s\Theta_{sd} \end{bmatrix} = G(s) \begin{bmatrix} s\Theta_m \\ -T_c \end{bmatrix} \tag{6}$$

where

$$G(s) = \begin{bmatrix} 0 & -e^{-sT} \\ e^{-sT} & 0 \end{bmatrix} . \tag{7}$$

It is straightforward to show that the corresponding scattering operator (4) is

$$S(j\omega) = \begin{bmatrix} -j\tan(\omega T) & \sec(\omega T) \\ -\sec(\omega T) & -j\tan(\omega T) \end{bmatrix} , \tag{8}$$

which has an unbounded norm implying that the system is not passive. In fact, one can show that

$$S^*(j\omega)S(j\omega) = \begin{bmatrix} \tan^2(\omega T) + \sec^2(\omega T) & \mathrm{j}2\sec(\omega T)\tan(\omega T) \\ -\mathrm{j}2\sec(\omega T)\tan(\omega T) & \tan^2(\omega T) + \sec^2(\omega T) \end{bmatrix} , \tag{9}$$

which has eigenvalues $[\tan(\omega T) \pm \sec(\omega T)]^2$ so that

$$\|S\| = \sup_{\omega} |\tan(\omega T)| + |\sec(\omega T)| = \infty . \tag{10}$$

Once again, this proves that the scattering operator is unbounded and hence the system is not passive. In practice, the signals entering the communication block are band-limited. However, since $|\tan(\omega T)| + |\sec(\omega T)| > 1$ for any ω, $T>0$ with $\omega T \neq n\pi$, the communication block is never passive for any range of frequencies. Furthermore, we would expect the instability problems to be most severe when $\omega T \rightarrow \pi/2$. Hence, the system will remain stable only if it exhibits extremely band-limited behavior [3].

Fortunately, the wave variable method can be implemented to stabilize a system. This is accomplished by using wave transformations on both the master and slave sides. The wave transformation relations for the single degree-of-freedom case are given by

$$\begin{aligned} u_s(t) &= u_m(t-T) \\ v_m(t) &= v_s(t-T). \end{aligned} \tag{11}$$

The wave transformations for the left wave junction are given by

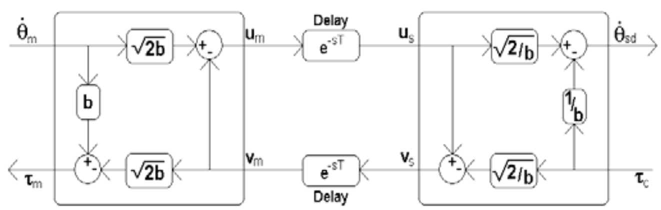

Figure 6: Wave transformations for a single degree-of-freedom teleoperation system.

$$\begin{aligned} u_m(t) &= \frac{b\dot{\theta}_m(t) + \tau_m(t)}{\sqrt{2b}} \\ v_m(t) &= \frac{b\dot{\theta}_m(t) - \tau_m(t)}{\sqrt{2b}} \end{aligned} \tag{12}$$

and that for the right wave junction are given by

$$\begin{aligned} u_s(t) &= \frac{b\dot{\theta}_{sd}(t) + \tau_c(t)}{\sqrt{2b}} \\ v_s(t) &= \frac{b\dot{\theta}_{sd}(t) - \tau_c(t)}{\sqrt{2b}} \end{aligned} \tag{13}$$

as shown in Figure 6. Although the strictly positive parameter b can be chosen arbitrarily, it defines a characteristic impedance associated with the wave variables and directly affects the system behavior [7]. The transfer system across the communication line now becomes

$$\begin{bmatrix} T_m \\ s\Theta_{sd} \end{bmatrix} = G_w(s) \begin{bmatrix} s\Theta_m \\ -T_c \end{bmatrix} \tag{14}$$

where

$$\begin{aligned} G_w(s) &= \begin{bmatrix} \dfrac{b(1-e^{-2sT})}{1+e^{-2sT}} & \dfrac{-2e^{-sT}}{1+e^{-2sT}} \\ \dfrac{2e^{-sT}}{1+e^{-2sT}} & \dfrac{1-e^{-2sT}}{b(1+e^{-2sT})} \end{bmatrix} \\ &= \begin{bmatrix} b\tanh(sT) & -\operatorname{sech}(sT) \\ \operatorname{sech}(sT) & \frac{1}{b}\tanh(sT) \end{bmatrix}. \end{aligned} \tag{15}$$

This can be easily shown by applying Mason's Gain Formula to the block diagram shown in Figure 6. Since sinh($j\theta$) = $j$sinθ, cosh($j\theta$) = cosθ, and tanh($j\theta$) = $j$tanθ, it follows that

$$G_w(j\omega) = \begin{bmatrix} jb\tan(\omega T) & -\sec(\omega T) \\ \sec(\omega T) & j\frac{1}{b}\tan(\omega T) \end{bmatrix}. \tag{16}$$

One can then verify directly that the norm of the scattering operator $S(j\omega) = [G_w(j\omega) - I][G_w(j\omega) + I]^{-1}$ is $\|S\| = 1$, which means that the system is passive and lossless. This is a somewhat tedious calculation; however, one can instead note that $G_w(j\omega)$ is skew-Hermitian and then use the fact that the scattering operator of any skew-Hermitian matrix is unitary and hence has a unit 2-norm, i.e., $\|S(j\omega)\|_2 = 1$, regardless of the value of ω.

While the previous calculations are at times tedious, it is instructive for students to verify the above results. Such an exercise would also allow an instructor the opportunity to reiterate certain important matrix theory concepts such as matrix norms and unitary matrices.

To incorporate the wave variable equations into the SIMULINK model, (12) and (13) are rearranged so they can be implemented using simple gain blocks. Figure 6 shows this simple configuration. Once the wave variable method is arranged in this form, it is easily implemented in SIMULINK as shown in Figure 7.

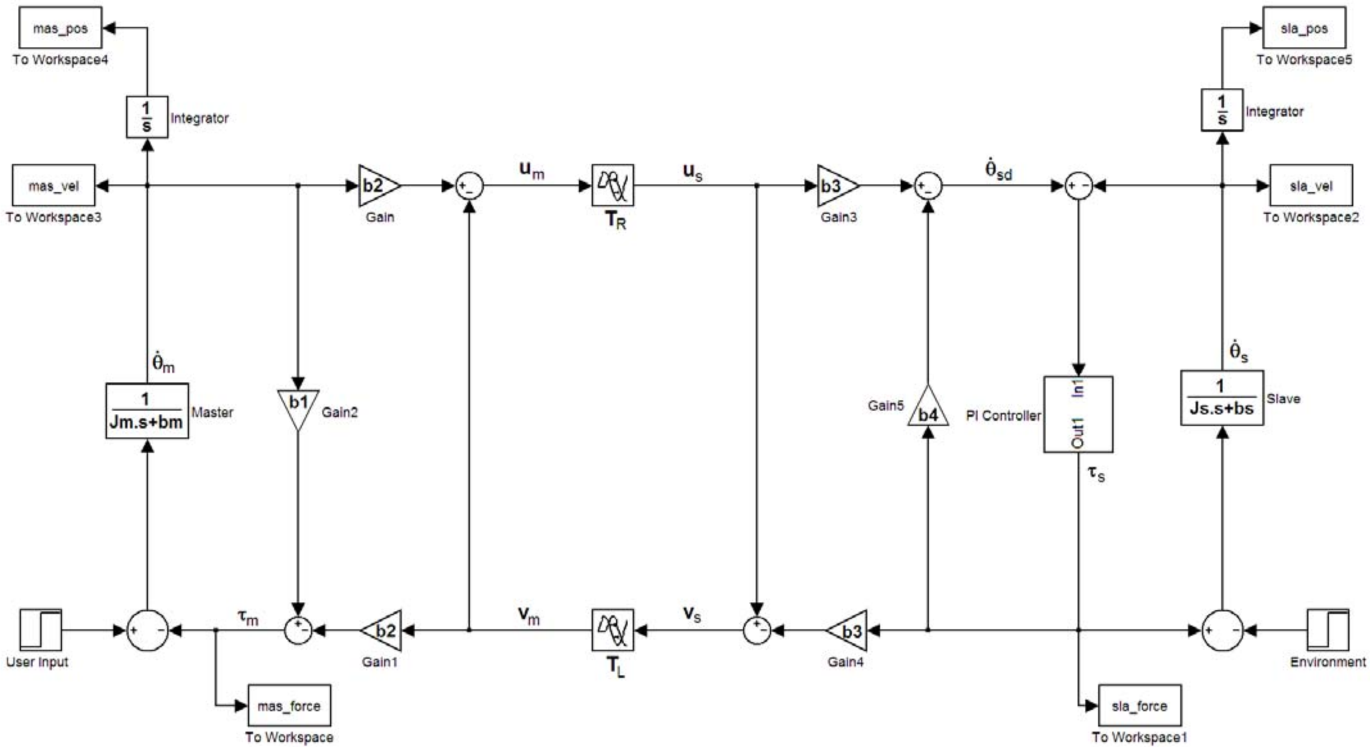

Figure 7: SIMULINK block diagram of a bilateral teleoperation system with time delay and the wave variable method. For the gain blocks shown $b1 = b$, $b2 = \sqrt{2b}$, $b3 = \sqrt{2/b}$, and $b4 = 1/b$.

Because wave variables are transmitted across the communication lines, the system is guaranteed to remain stable for any fixed time delay. As can be seen in Figure 8, the system indeed remains stable, and the torque, position, and velocity of the slave clearly follow those of the master. If these results are compared to the original system without any time delay present, it can be seen that the general trends are preserved; however, there is a slight degradation in performance, both with respect to peak overshoot and settling time. This compromise of system performance for guaranteed stability is a natural part of control system design. Overall, even with these performance issues it can be seen that the system with the wave variable method yields more desirable results for a teleoperation system that may experience time delay.

A natural step after addressing issues associated with constant time delay is to consider teleoperation systems experiencing varying time delay. This occurs for example when the Internet is used for the communication link. This requires more advanced techniques since, without modification, the wave variable method can only guarantee stability in the presence of a fixed time delay. Schemes using additional elements such as observers and Kalman filters as estimators have successfully stabilized teleoperation system using the Internet [5]; however, the issue of system performance is still an ongoing research problem.

Conclusions

In summary, we have described the Matlab and SIMULINK tools necessary to simulate and control a bilateral teleoperation system. Matlab was used to set up the parameters of the system, and SIMULINK was used to set up the connections between the master and slave models and to simulate the overall system. After simulating a simple teleoperations system

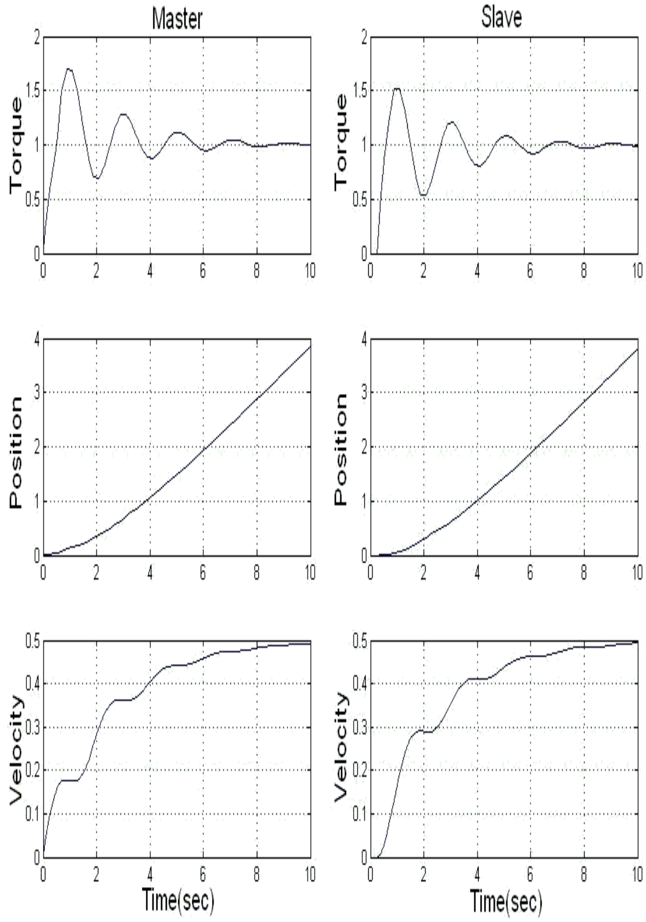

Figure 8: Torque, position, and velocity data for the simulated model of a bilateral teleoperation system with a time delay given by *2T=500msec*, now with the wave variable method implemented.

operating under ideal conditions, time delay was introduced into the communication link of the model. It was shown that even a modest amount of time delay can be detrimental to teleoperation system using force feedback. A relatively new technique for handling time delay called the wave variable method was then implemented to stabilize the teleoperation system with time delay.

The material presented in this article should be suitable for inclusion in an undergraduate or first year graduate course in control systems. The material only requires access to a PC with computer software such as Matlab with SIMULINK. Other possible problems to include in a classroom project are noise compensation and variable time delay. Although this article focused on single degree-of-freedom systems, the system described here can be extended to a multiple degree-of-freedom system [1, 2].

Acknowledgment

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